Coordinating procedural and conceptual knowledge to make sense of word equations: understanding the complexity of a ‘simple’ chemical task at the learner’s resolution

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Abstract

This paper discusses the conceptual demands of an apparently straightforward task set to secondary level students – completing chemical word equations with a single omitted term. Chemical equations are of considerable importance in chemistry, and school students are expected to learn to be able to write and interpret them. However, it is recognized that many students find them challenging. The present paper explores students' accounts of their attempts to identify the missing terms, to illuminate why working with chemical word equations is so challenging from the learner's perspective. 300 secondary age students responded to a 5-item exercise based on chemicals and types of reactions commonly met at school level. For each item they were asked to identify the missing term in a word equation, and explain their answers. This provided a database containing more than a thousand student accounts of their rationales. Analysis of the data led to the identification of seven main classes of strategy used to answer the questions. Most approaches required the coordination of chemical knowledge at several different levels for a successful outcome; and there was much evidence both for correct answers based on flawed chemical thinking, and appropriate chemical thinking being insufficient to lead to the correct answer. It is suggested that the model reported here should be tested by more in-depth methods,

but could help chemistry teachers appreciate learners' difficulties and offer them explicit support in selection and application of strategies when working with chemical equations.

key words: chemical equations, word equations, student thinking, expert/novice thinking; strategic/tactical thinking

Introduction

This paper discusses how students make sense of word equations. The paper presents an analysis of secondary level student responses to the apparently straightforward task of completing word equations with a single omitted term. A set of five such exercises was attempted by 300 students who were expected by their teachers to be able to work with word equations. They were asked to name the missing substance, and to explain their answers. The exercises were designed to reflect substances and reaction types likely to be familiar from school science. A fifth of the suggested answers were considered to be incorrect (about two thirds of responses were classed as correct, and the remainder as 'nearly' correct – see below). As chemical equations are ubiquitous in teaching and learning chemistry, and are used to represent the key processes of the subject (chemical changes), this was considered worthy of closer investigation. As we will discuss in this paper, our analysis of students' reasons for their responses suggests that correct responses on these very simple completion tasks are often achieved despite thinking that is inappropriate or at least incomplete from a scientific perspective.

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It is suggested here that this particular task, completing word equations based on familiar types of reactions, is one that would seem trivial to the expert (the chemist, or science teacher), but offers significant difficulties to learners. This being so, effective teaching requires the teacher to be aware of, and take into account, the complexity of working with word equations. The present paper, then, explores why such a 'basic' tool for learning and discussing chemistry proves to be problematic at 'the learners' resolution'. This is undertaken through an analysis of the task, drawing upon the reasoning students reported.

Expert and novice thinking

Expert thinking is qualitatively different from novice thinking (Baron, 1994) in ways that can make it difficult for the expert to appreciate the difficulty of the task for the novice. Expertise is developed over extended periods of time when someone engages regularly and deeply with a field (Gardner, 1998). There are at least two aspects of expertise that may be relevant to the present study – relating to the conceptual and cognitive aspects of the scientific task. Firstly, experts develop an extensive and effectively structured knowledge base in the field (Mayer, 1992). Due to extensive consolidation of knowledge, much of this is very readily accessible. The same nominal working memory capacity is able to manipulate much more complex information when it is dealing with well-consolidated knowledge (Sweller, 2007).

Experts are also able to 'automate' processes. The expert is not only able to see whole patterns as single entities, rather than complex configurations, but is also able to combine sequences of actions into a single process. This latter effect is perhaps most familiar in the sensori-motor domain, where practice allows complex sequences of muscle contractions to be organised into modules that effectively become a single operation (e.g. in learning grasp a toy, in walking, typing, driving, playing sports etc.)

The role of chemical equations

Chemical equations are used to describe chemical reactions, and are commonly of two types, word equation and formulae equations. Both types are used in secondary education (e.g. in the UK where the present study was undertaken), with formulae versions based on alphanumeric formulae for substances. Word and formulae equations can readily be written for most of the chemical changes studied in school. For example, the combustion of methane may represented as

methane + oxygen → carbon dioxide + water

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

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Both forms would be considered as valid representations of the chemical reaction. The terms of such equations represent substances, such as the compound methane and the element oxygen, the reactants in this particular example. The formula equation is more abstract than the word equation (with single substances often represented by compound formulae such as $CuSO_4$), and needs to be balanced, but offers explicit information about the elements 'represented' in the substances involved.

The official guidance document on teaching lower secondary science in England (ages 11-14) refers to how "pupils need to learn to represent compounds by formulae and to summarise chemical reactions by word equations" (DfES, 2002: 15). This document suggests that the notion of a word equation should become part of the students' vocabulary in the first year of secondary education (p.74), and then within two years "pupils should be taught to write word and symbol equations for some simple reactions" (p.28).

Reasons to expect learning about chemical equations to be problematic

Although word equations may seem relatively straightforward, there are good reasons to expect students to find them a challenging aspect of school science. This is a topic which has attracted limited explicit attention, yet there is a good deal of research demonstrating that students have difficulty with the fundamental concepts which are needed to make sense of the chemical reactions represented in the equations.

It is known that students do not readily acquire the fundamental concept of chemical substance without which chemical reactions have little meaning (Johnson, 2005). Therefore it is not surprising that a range of research studies has shown that students form various alternative notions of chemical change that do not fit scientific understanding (Ahtee & Varjola, 1998; Andersson, 1986; Briggs & Holding, 1986; Cavallo, McNeely, & Marek, 2003; Hesse & Anderson, 1992; Johnson, 2000). Many 14-15 year-olds have not developed clear distinctions between chemical and physical changes (Watson & Dillon, 1996). Limited, atheoretical, thinking about chemical change has been found among many 16-18 year olds (Barker & Millar, 1999; Solsona, Izquierdo, & de Jong, 2003; Taber, 1996), and even among university students (Ahtee & Varjola, 1998).

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So, basic conceptual frameworks that make sense of the chemical reactions that equations represent may not be well developed in many students at secondary level when chemical equations are taught.

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There may also be additional challenges for many students in working at the representational level in chemistry. In learning about chemistry, students are asked to make repeated shifts between discussion of materials that they can see, smell and handle; various abstract representational models; and explanatory models based on conjectured entities at sub-microscopic scale (Jensen, 1998), and this is considered to contribute to the difficult of learning about the subject (Gilbert & Treagust, In preparation; Johnstone, 1991).

Yet research suggests that an understanding of the basic chemical concepts of substance and chemical reaction may depend upon developing mental models of the phenomena through the use of particle models (Johnson, 2002; Taber, 2002b), when it is well established that these models are themselves highly counter-intuitive for many learners (Adbo & Taber, 2008; Ault, Novak, & Gowin, 1984; García Franco & Taber, Accepted for publication; Griffiths & Preston, 1992; Nussbaum & Novick, 1982; Taber, 2001a, In press).

The symbolic language of chemistry

Even remaining within the representational level, the demands of working with such formalisms may be quite high. Students find it difficult to construct word equations (Soul, 2001), or to interpret them in terms of what is happening in a reaction (Kearton, 2002). Students not only find difficulty in writing formula equations from word equations (Hines, 1990), but also in writing word equations when given formulae equations (Howe, 1975).

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Chemical equations, whether substances are represented by words *or* formulae, are part of the specialist *language* of chemists and science teachers (Taber, In preparation, In press), and from the perspective of these 'experts' are a simple way of representing the way chemical reactions involve changes of some chemical substances (reactants) into others (products). To such an expert, the equation offers a straightforward representation of a chemical change that can be readily related to both bench phenomena (i.e. the production of new chemical substances with properties that differ from the reactants), and to models of how such change involves interactions between the sub-microscopic entities (molecules, ions etc) from which the reactants

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are composed to give the new sub-microscopic entities that comprise the new substance(s) produced.

However, a novice who lacks a suitable understanding of the scientific concept of substance, and does not have available the appropriate mental imagery (Gilbert, 2005) of scientifically sound particle models to support an appreciation of the essential nature of chemical change, may not have the conceptual resources upon which to draw when asked to produce or interpret chemical equations (Taber, 2007/2008).

The reference to a chemical *language* is intended to be more than an analogy (Taber, In press), and unless teachers are able to take full account of the demands made of students, then - for many learners - the study of chemistry may well be an experience of learning unfamiliar ideas through the medium of an unfamiliar language, as taught by a subject expert who is fluent in both the ideas and the language used to present them.

It seems quite likely that many *experts* (e.g. chemistry teachers) would be able to complete simple word equations such as those discussed here without *consciously* applying any rules or other heuristics. This material is so familiar and basic that such experts often 'see' the answers instantly. This does not mean that there is no thinking involved, just that it has become so automatic that it occurs pre-consciously (Cohen, 1983). Whilst such close familiarity with the material is an important part of a teachers' subject knowledge, it is also important for the teacher to be able to appreciate the nature of these tasks 'at the learners' resolution', i.e. the conceptual and cognitive aspects of the tasks when undertaken by the students who lack such expertise. It is such a task analysis that is the basis of the present study.

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The context of the present study

The present study derives from a project funded by the Royal Society of Chemistry (RSC) to support teaching of chemistry topics in secondary schools in the UK. The first author undertook the 'Challenging Chemical Misconceptions' project (Taber, 2001b) on behalf of, and whilst on secondment to, the RSC. The project set out to support teaching about key chemistry topics where it was known that learners often misunderstood or failed to make sense of the concepts in the curriculum. During the project, materials were prepared to help teachers diagnose common alternative conceptions and other conceptual problems in chemistry topics, and to offer support in helping students develop chemical concepts. The diagnostic materials were made available via the worldwide web (Royal Society of Chemistry, n.d.-a) and published in book form (Taber, 2002a) with an accompanying volume explaining the nature of student conceptual problems and offering suggestions for using the materials in teaching (Taber, 2002b). One of the topics chosen for inclusion in the project was that of word equations.

The Challenging Chemical Misconceptions project was primarily intended to develop teacher support materials, rather than as a research project. However, it was important that all published materials were trialed, and were found to be useful by classroom teachers. The project therefore recruited school and college chemistry and science teachers who were interested in trying out classroom materials, through an invitation in practitioner journals. These teachers were informed about the topics and target age ranges (11-14, 14-16 or 16-18) for which materials were being prepared, and asked to suggest where they could try materials with their classes. Pilot materials were sent to teachers with the request that completed materials be returned along with a completed

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feedback sheet. This therefore generated material that could be used to evaluate the usefulness of the materials, but also a database of student responses that could be interrogated.

The rationale for the diagnostic instrument, along with brief discussion of some of the responses from a single teaching group, were included in the RSC book (Taber, 2002b: 141-4). The present paper draws upon the responses from students from 18 teaching groups. Participating teachers were aware that responses could be used in research intended to inform teaching.

The diagnostic instrument

A simple instrument was prepared to diagnose whether students could make sense of word equations (Taber, 2002a), (Royal Society of Chemistry, n.d.-b). The instrument had five items based around incomplete word equations. For each item, the students were asked to complete the word equation, and explain how they came to their answer.

The word equations were selected to include substances and reaction types that are met in school chemistry. The items were:

1. nitric acid + potassium hydroxide → ____________ + water

2. zinc + ____________ → zinc nitrate solution + copper

3. ____________ acid + zinc carbonate → zinc sulphate + water + carbon dioxide

4. calcium + chlorine→ ____________

5. magnesium + hydrochloric acid→ ____________ + hydrogen

The following general instructions were given:

"Word equations are used to describe chemical reactions. Look at the word equations below. In each case complete the word equation by adding the name of the missing substance. (Explain your answers if you can.)"

After each of the five items, the following stem was provided: "I think this is the answer because". This was followed by a lined space (about three and a half lines) for completion.

The sample

By the nature of the project, the sample is a convenience sample, being made up of students in classes volunteered by their teachers to trial materials for the project. Although teachers reported the nature of their classes differently, the information they provided suggested that the materials were used by students across the ability range. Those teachers of the students in the sample for the present study who described their classes in 'ability' terms (12 of the 18 classes) variously reported them as being high/top (4 classes), middle/intermediate (2), low (3) or mixed (3) ability. The size and diversity of the sample mean that the findings are suggestive of what might be found in a more representative study of secondary learners studying in the English curriculum context.

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Data was collected from a total of 300 students, from 18 different classes in twelve different institutions. (Eleven institutions were based in the UK. The exception was an English language international school elsewhere in Europe). Ten of the groups (184 students) consisted of Y9 students (13-14 year olds), and one group of 10 students

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were 16-17 year olds. The remainder (106) consisted of upper secondary (14-16 year old) students.

Student success in completing word equations

As 300 students responded to a 5-item test, there were potentially 1500 responses to consider. Of these there were 87 (about 6%) omitted items where no answer was offered. About two thirds (916, 65%) of the answers that were offered were judged correct, and a fifth (283, 20%) incorrect. The other 15% (216) of responses were considered 'almost' correct: that is, technically wrong, but considered close enough to the correct answer to be credit-worthy. Some items were answered correctly more often than others. Table 1 shows the number of correct responses to the different items.

Table 1: Completing the word equation

The number of responses to each item ranged from 279 to 289 (see Table 1). Item 4 (concerning the simplest reaction type: binary synthesis) was answered correctly by almost nine tenths of those responding to the item. However, the success rate was lower on the other items. For items 3, 1 and 5 the proportions giving the correct response were approximately four-fifths, three-quarters and two-thirds respectively. Most of the 'nearly correct' responses were on item 2, where most responses were categorized this way. In fact the 'error' in all of the 'nearly correct' answers in item 2 was to omit reference to the missing reactant being in solution. The reaction would not readily occur if the reactants were both solids, and it would be impossible to have a solution as a product. However, these 'nearly correct' students did suggest which salt would need to react. For the purpose of the qualitative analysis below, these responses are treated as if correct.

Overall, this shows that given simple completion items, most respondents were able to offer a correct or nearly correct responses. However, if the item non-responses are assumed to indicate the student could not offer any answer, then about a quarter of the possible responses were not even close to a correct answer. Given the intended straightforward choice of the task, and the diverse nature of the sample, this suggests that many secondary students may have serious difficulties understanding word equations. This is considered worthy of further investigation, and leads us to ask:

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- Why do students who have been introduced to word equations make errors in 'simple' completion exercises, i.e. those that involve familiar classes of reactions and common reagents?
- In particular, what is the nature of the task when understood from 'the learners' resolution' that makes apparently trivial questions demanding to many learners?

We will suggest below that that fairly high success rate on most of these items cannot be taken to imply a high level of understanding of the underlying chemical principles. Students report a range of strategies to completing the items, some of which can not reliably ensure correct responses, and some of which are likely to be less effective in more demanding questions (such as completing word equations with two missing terms).

Methodology

An analysis of the task was carried out in terms of an examination of the reasons students gave for their answers. There were 300 students each presented with 5 items, so potentially 1500 responses. Responses to the request for reasoning were offered for almost three quarters of the items (1093, 73%). A small number (n=6) could not be meaningfully interpreted as sensible answers. This provides a database of over a thousand examples of student reports of their thinking.

A quantitative analysis is not offered here, for a number of reasons. Firstly, the purpose of the present paper is to offer an exploration of the complexity of the task when perceived from the learner's perspective. Secondly, although the database is considered to be a rich source of insights into the way students were making sense of the task, and so of word equations, the nature of the data and the method in which it was collected (written answers) limits its potential to reveal the full thinking processes by which students completed the exercises.

Even if assumptions are made that students were conscientious in reporting their reasoning (and it is quite possible that some non-responses were due to a lack of motivation rather than not being able to offer any reasoning), it will become clear that a full report of the thinking needed to answer these straightforward questions can become quite involved. Students' responses are accounts limited to the aspects of their reasoning that they were explicitly aware of (i.e. excluding steps made at a subconscious level), and may well exclude aspects of the process that might be considered obvious and not worthy of being stated.

Indeed student reports, as well as being partial, may often be the subsequent explicit rationalisations of their thinking, which may not reflect the actual thinking processes that produced their answers. (In effect, the accounts concern the 'context of justification' not the 'context of discovery'.) Given these uncertainties, which are revisited in the discussion, the database has been interrogated by an interpretive (Strauss & Corbin, 1998) or 'exploratory' (Taber, 2007) approach, aiming to identify the main strategies that students report using, and the types of chemical knowledge they cite in their reports. The analysis drew upon grounded theory approaches to the interpretation of qualitative data (Taber, 2000), designed to build a model that could encompass all the data. That is, the data was revisited and the model adjusted until it was considered that the model fitted all the data.

Although the outcome of this analysis, reported below, was a set of seven reported strategies, these were not considered as a set of *exclusive* categories into which each datum could be assigned, but rather a representation of the overlapping and complementary conceptual resources that students variously drew upon in their reported rationales. This lack of 1:1 mapping of data to categories is not considered as a flaw in the analytical scheme, but rather a necessary feature of a model that reflects the complexity of the task when considered 'at the learners' resolution'. This is a point that will be illustrated in the presentation of our findings.

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The findings from the analysis are reported in the next section. In responding to the qualitative researchers' dilemma (Pope & Denicolo, 1986) of balancing detail with data-reduction, a limited number of exemplars are discussed in the text, supported by tabulation of sufficient illustrative examples to give an impression of the range of responses in each category.

Findings

The student reports demonstrated application of one or more of a limited number of types of strategy:

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- Recall Strategy: recall the reaction/equation. For example, one student giving the correct response in the first item (*potassium nitrate*) explained "that's what I remember from class".
- Schema Strategy: use a reaction-type schema (patterns based on types of reactions). For example, one student explained the rationale for a correct response on the first item, as "the acid is neutralized by the alkali to make water and a salt will be made".

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- Classification Strategy: apply patterns found among classes of substance (such as metals or a acids). For example, one student correctly answering item 5 explained that "when metals react with acid they give off hydrogen"
- Behaviour Strategy: apply patterns related to the substance. For example one student correctly answering item 5 explained that "the magnesium displaces the chloride from the hydrochloric acid as it is more reactive".

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- Conservation strategy: use the conservation principle to suggest elements that need to appear in the missing term. For example, one student correctly responding to item 2 explained "in the result there is zinc and copper and to make that you need zinc and copper in the first place"

- Narrative Strategy: involve devising a feasible account of what occurs during a reaction. By feasible, we mean a story that made sense to the student, rather than one which would necessarily be considered a viable chemical mechanism. For example one student who correctly identified calcium chloride as the product in item 4 suggested that "the chlorine mixes with the calcium and dissolves it to become joined".

- Intuitive Strategy: rely entirely on pre-conscious thought. Most generally, this meant relying on guesses and being able to offer no other reason for the particular response guessed.

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One key issue that we will highlight in presenting our findings is that with some of the strategies discussed here, there was often limited linkage between correct answers and sound chemical reasoning. That is, we found that correct answers were often obtained by students who gave faulty reasoning; and that applying correct chemical knowledge (principles or facts) was often insufficient to allow a student to correctly identify the missing term in the equation. We will explain below why this is to be expected from novices lacking the extent and organisation of subject knowledge of an expert, even when the strategies themselves are fundamentally sound.

This is related to our finding that it was common for students to explain their thinking through a combination of several of these strategies. As we will argue below, such a 'meta-strategy' may often be a sensible approach where the student is not able to access the range of chemical knowledge that would allow an expert to readily identify the missing chemical term. In the discussion section below we will present a scheme that teachers may use to support novices tackle the task of completing word equations (see figure 1). This is a model of an optimum approach based upon our analysis of the

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way students responded to this task. It may be that some students in our sample were explicitly or otherwise using such a scheme, but the present study does not allow us to make such a claim. What was clear was that many students in our sample commonly combined several of the discrete strategies we identify here, as our analysis will highlight.

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Recall Strategy

One strategy that was reported by students was simply to remember the reaction, or its equation. Clearly accurate recall would allow the missing term to be readily identified. This was not a strategy reported by many students, although it is quite possible that it was used in some cases where no rationale was offered.

Students giving the correct response in the first item (*potassium nitrate*) explained the response in terms of "seen it before" and "I can remember it from my book and when you combine these chemicals you produce those other chemicals". Students who had "memorized it", cited several different sources:

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> "at some point someone (probably a chemistry teacher) told me that this is what happens"

> "I remember this from having read it in the textbook"

> "I have done this experiment before…Memorized before".

In item 3, two of the students correctly identifying the missing term as *sulphuric* (acid) reported their reasoning as:

> "Displacement reaction. Also memorized it."
>
> "In class we discovered that all acid contain H. It's hard to explain but I guess I just memorized it."

Both of these responses included two aspects to the answer. The first response draws on the type of reaction (i.e. the schema strategy), and the second on a common chemical pattern (classification strategy). As we noted above, the combination of more than one strategy was a common feature of student responses.

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The recall strategy is clearly an effective one when recall is accurate, but only of value when the actual reaction has been learnt. As there are a potentially huge number of reactions that school students could be expected to know about, this is clearly not a strategy that can be relied upon.

Schema Strategy

The schema strategy is of particular interest because this reflects the approach that had guided the design of the task (Taber, 2002b). School students are expected to learn a small number of common basic reaction types from inorganic chemistry, which can act as general schemata. Students would be expected to be able to complete equations showing either only reactants or only products, whereas the items discussed here (apart from the simplest, item 4) provided redundant information.

Successful application of the strategy requires coordination of knowledge about a general equation that only refers to classes of substance, and about the specific substances in that particular example of the class of reaction. So for item 1, the schema strategy would identify this reaction as an example of a general type of reaction (i.e. applying knowledge of a chemical pattern) that has the form:

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acid + alkali → salt + water

Identifying the acid as nitric acid and the alkali as potassium hydroxide (using knowledge of the pattern that hydroxides are alkalis), leads to the identification of the missing term as being a salt. Knowing that the salt produced will be named after, (a) firstly the metal deriving from the alkali and (b) then the acid radical; and that (c) nitric acid gives nitrates (i.e. applying knowledge of chemical patterns, cf. classification strategy below) leads to the conclusion that here the salt will be *potassium nitrate*.

Table 2: Examples of students rationales based on type of reaction schemata.

Although there were some exceptions, student reports suggesting a use of this approach were largely associated with correct responses (see examples in Table 2). Student accounts of their reasoning included those that simply gave the general equation ("acid + base = salt + water") or an equivalent statement ("when an acid is reacted with base we are left with a salt and water"), and those that included additional detail:

> "an acid and an alkaline have reacted, meaning a salt will be produced. The reactants are nitric acid and potassium hydroxide, so the product will be potassium nitrate"

Clearly recalling the general equation by itself does not give the answer unless the specifics of the known reagents are also considered. The rationale that "when you add an acid and an alkali you get a reaction which produces salt and water" led one student to the incorrect (i.e. non-specific) response *salt*. Student reports only offer limited insights into actual thinking processes, and many offered the correct response, despite limiting their accounts to the general nature of the reaction (see Table 2).

However, many of the rationales for the correct responses included a 'mix' of strategies drawing upon knowledge of more specific chemical patterns:

> "Acid + hydroxide = salt + water. Nitric acid gives nitrates"

> "oxygen and hydroxide make water and the anything left is nitric and potassium. It is also a reaction between an acid and an alkaline"

Similar findings were found for the other items, with student accounts of their thinking variously offering just general equations or various supplementary rationales (see Table 2).

One student, who applied the schema strategy in item 2, used it alongside the conservation strategy: "it is a displacement reaction. If copper and nitrate are at the end they must be present as part of the things combined". Another response seemed to offer features of three strategies:

> *copper nitrate (aq)*: "copper is left over [conservation]. It is a displacement reaction [schema]. The zinc is higher in the reactivity series [behaviour]"

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Interestingly, on item 2, students citing the category of reaction tended to refer to the difference in reactivity between copper and zinc: something that 'explained' why the reaction occurred - but was not necessary to explain how the missing substance was identified:

copper nitrate solution: "it is a displacement reaction. The zinc is more reactive than the copper and 'wins' the nitrate solution making zinc nitrate solution"

This tendency to 'explain' the reaction is linked to the strategy here labelled 'narrative' (see below).

The application of the schema strategy sometimes led to a correct answer, even when the general reaction is mis-recalled, as by the student who explained that "when a metal reacts in acid a base [sic] is formed with a hydrogen gas produced", or another who claimed "a metal dissolves in an acid produces a salt and water …". Another student justified a correct answer with a somewhat muddled general reaction: "the acid reacts with the salt to get a base and water and CO_2".

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Making an error in recalling the general form of the reaction can clearly also lead to getting the answer wrong, as when the general form "acid + metal = salt + water + hydrogen" led to a response of *magnesium chloride* + *water* on item 5. So, although generally a successful strategy, the use of reaction type schemata was not fail-proof. One respondent using this strategy selected the wrong salt, so although reporting that "I know an acid reacting with an alkali = a salt and a water", the answer given for item 1 was *potassium nitride*, an illustration of how successful use of the strategy requires a coordination of chemical knowledge. (It is not possible to know whether this respondent appreciated the distinction between the nitrate and nitride, or if this was just a linguistic slip: either way this would be judged a wrong answer in a formal test.)

Identifying the wrong reaction-type schema could sometimes still lead to the right answer ("if the potassium hydroxide was oxidized it would turn into water you would then be left with potassium nitrate"), but clearly might not, as when the rationale "this [item 2] is an oxidation" leading to the incorrect response *copper oxide*.

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Classification Strategy

The schema strategy is based upon recognising particularly important types of chemical patterns, allowing a vast number of possible reactions to be represented by a much more limited set of general schemata. However, there are many other less general patterns in chemical behaviour that can offer clues to what is going on in chemical reactions.

There are linguistic patterns found in chemistry, and 'grammatical' patterns that can be used as clues. These types of patterns were cited by students correctly answering several of the items (mainly in items 1, 3 and 4 – see Table 3). They are not in themselves logically sufficient to lead to correct responses, and so need to be used (consciously or otherwise) alongside other strategies to avoid incorrect responses. So *potassium nitric* was offered as an answer for item 1 because "if you take the main component of each equation (i.e. nitric acid) and join them together you should get it"; one respondent used the clue that "nitrate sounds like nitrogen" to give the answer *nitrogen* in item 2; and another drew upon the idea that "-ide is for two and that is the acid" to support the incorrect response *magnesium hydroxide* in item 5.

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Table 3: Student rationales based on patterns in chemical language

There are also general patterns relating to classes of substance, for example, acids (as understood at school level) contain hydrogen; particular acid radicals are found in compounds deriving from reactions of particular acids; and so forth. Therefore, identifying a substance as being part of a wider class can allow the student to infer that the substance will fit a pattern known to apply to that class of substance. This strategy was cited across all five items in support of correct responses, as shown in Table 4. These patterns again offer insufficient information to determine the correct response, but may be used in conjunction with a complementary strategy, such as applying the conservation principle, e.g. justifying *potassium nitrate* in item 1:

> "the nitric acid reacts with metal oxides [sic] to produce nitrates and the hydrogen and oxygen in the potassium hydroxide went into water. So potassium is left to react with the nitric acid"

Some of the rationales offered to support correct responses are chemically invalid; for example, it is not the case that when hydroxides react they usually give nitrates, nor that potassium hydroxide is a salt; or that reactions of sulphuric acid will always give carbon dioxide (see Table 4). So although these ideas may have helped lead students to the correct response in these particular cases, it was not surprising to find similar arguments in support of incorrect responses. For example, several of the responses to item 2 cited in Table 4 support the incorrect response *nitric acid* in terms of the reasonable link between that acid and nitrates.

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Table 4: Examples of student rationales for correct and incorrect responses based upon patterns in behaviour of classes of substance

One response for item 5, justifying the answer *magnesium chloride* combined knowledge of a class of substances (acids) with a dubious narrative describing the process: "all acids include hydrogen and this is where the hydrogen comes from. The chlorine joins itself to magnesium by dissolving it."

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Behaviour Strategy

As well as reporting rationales based on patterns in chemical reactions, and patterns in the behaviour of classes of substance, students also supported their answers with reference to the specific properties of particular reactants. Some illustrative examples are included in Table 5.

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Table 5: Examples of students' rationales for correct and incorrect responses based upon chemical behaviour of substances.

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A particularly popular notion that students drew upon was the reactivity of a substance, or the relative reactivity of competing substances. Table 5 includes a number of examples of different phrasing based on this argument for the correct response in item 1. However, these rationales were commonly of the form that "potassium [sic] is higher in the reactivity series than the acid so it displaces it", or "hydrogen is more reactive than nitrogen, so is potassium and therefore it takes the nitrogen away". These rationales generally considered potassium to be a reactant, whereas the reaction actually concerned potassium hydroxide, a very different substance. So item 1 was here answered correctly by students who had a fundamental misunderstanding of the nature of how elements are represented in compounds, a very basic chemical principle.

Students holding this flawed conceptualisation of how compounds behave during chemical changes, were able to access a correct but irrelevant chemical fact (potassium is reactive) to construct narratives (see below) to make sense of the reaction. The high reactivity of potassium supported both correct and incorrect responses:

> "[*potassium nitrate* because] the potassium reacts strongly with the acid and hydrogen and oxygen leave the potassium to make water, potassium is highly reactive"

> "[*potassium* because] potassium is higher than nitric acid in the reactivity series so therefore the potassium will displace the nitric acid"

As the examples in Table 5 show, a range of incorrect responses were supported by this argument.

Table 5 also presents some examples of students supporting their responses by arguments based on other aspects of chemical behaviour of particular reagents. Such arguments included both relevant patterns ("hydrochloric acid forms a 'chloride' salt") and some dubious chemical arguments being used to support correct responses ("calcium will mix with oxygen and chlorine to form a chloride"). It is not clear how the *correct* response to item 1 (*potassium nitrate*) is supported by the explanation "because the potassium hydroxide and nitric acid combine to make potassium oxide".

Deleted: Table 6: Examples of student's reported rationales for correct and incorrect responses based on patterns of behaviour of specific substances¶

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Some of the examples in Table 5, such as the affinity of potassium for nitric acid or the acidity of chlorine, do not reflect chemically sound thinking. For example, one rationale offered for the formation of calcium chloride (item 4), was that:

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> "the elements react to gain a full outer electrons shell causing the elements to become positive and negative ions and opposites attract"

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This reference to elements gaining full electron shells reflects the common octet framework (Taber, 1998) where reactions are conceptualised in terms of an presumed initial atomicity of elements. Similarly, drawing upon appropriate chemical patterns, such as hydrogen deriving from the acid in a reaction (item 5), does not ensure a correct response.

Conservation strategy:

The previous strategies were based upon applying knowledge of patterns of chemical behaviour at different levels of generality (of reaction types; or classes of substance; of specific substances). The next strategy examined is that of applying the fundamental chemical principle that the same elements are represented after the reaction as before or that "everything on the right hand side goes on the left", as one student explained (Table 6).

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Table 6: Examples of students' rationales for correct and incorrect responses based upon the application of a conservation principle.

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A strength of this principle, is that it always applies to any chemical process, and it was cited by students in each of the items:

potassium nitrate (item 1): "hydrogen and oxygen make water – potassium is left over and so is nitric acid put them together - get potassium nitrate"

aqueous copper nitrate (item 2): "zinc nitrate solution and copper minus the zinc leaves nitrate solution and copper. Therefore as there is only one space these two go together to form copper nitrate solution"

sulphuric [acid] (item 3): "the sulphur in zinc sulphate must have come from somewhere as must the hydrogen in the water. Sulphuric acid contains sulphur and hydrogen"

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calcium chloride (item 4): "these are the only two things that can react and they don't give off (make/produce) any other products"

magnesium chloride (item 5): "what is on the left must also be on the right. The hydrogen in the acid is released as a gas leaving magnesium and chlorine these will form magnesium chloride"

In item 3, the response options were considerably reduced through students being given the clue that they were looking for an acid. As one student explained "I thought where does the sulphate come from, it can't come from nowhere and also there was a space for a type of acid".

A major limitation of this strategy is that although it restricts possible answers, it usually leaves open a range of possibilities. One student reached the correct response (*potassium nitrate*) in item 1 apparently by ignoring the presence of hydrogen in the acid: "because I'm left with potassium and nitric acid but nitric acid makes nitrate when the reaction happens". Another student argued for the correct answer that "nitric acid contains hydrogen, nitrogen and oxygen and potassium hydroxide contains potassium, hydrogen and oxygen. Water is hydrogen and oxygen, so the leftovers, potassium and nitrogen bond". This seems to imply there is no oxygen represented in the nitrate, i.e. that a mistaken deduction has been cancelled by an error in applying that deduction.

Applying the strategy could lead to the correct response, even if supported by dubious chemical knowledge (e.g. "the only thing left is an acid and magnesium therefore hydrogen has already been taken away leaving chloride and magnesium, which is an acid", item 5). However, the strategy could also lead to incorrect responses when misapplied: "the hydrochloric acid produces hydrogen the only thing left is magnesium". This strategy may be used in combination with other strategies, so that another student, who seemed to initially follow the same flawed logic (in item 1), then modified the argument, drawing upon knowledge of chemical language, i.e.

> "the hydroxide and the acid bits are made up of hydrogen and oxygen, which make water. The remaining bits therefore must combine to make something which is potassium and 'nitric' which is nitrogen and you write it nitrate. It is nitrate because there is some oxygen left over I think"

Such hybrid answers were also found in other items, e.g. (in item 2):

> "you need nitrogen to make zinc nitrate and copper for the outcome, copper is less reactive than zinc so the nitrate leaves the copper and goes to the zinc".

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A mechanistic narrative was offered by one student applying the conservation principle in item 3, another example of a correct response based on a somewhat dubious rationale:

> "to make zinc sulphate you need zinc and sulphur, there is zinc in zinc carbonate and there is sulphur in sulphuric acid so they join up. There is water in acid so that is made and also the carbon in zinc carbonate joins up with the oxygen in the acid to make carbon dioxide"

Narrative Strategy

Some student accounts offered a 'story' about the chemical change involved, without explicitly referring to chemical patterns such as the chemical behaviour associated with a class or chemical or particular reagent. Such narratives were offered across the five items (see Table 7).

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Table 7: Examples of students' rationales for correct and incorrect responses supported by narratives

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Sometimes students offered what seemed irrelevant supplementary information, as in this example (for item 3):

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> "when an acid reacts with the carbonate, water, carbon dioxide and a base is formed. We can test for carbon dioxide by taking a sample of the gas and bubble it through limewater if carbon dioxide is present the limewater will turn milky"

Although not seeming relevant to the task it may well be that some students learn about chemical reactions as a series of narratives, so forming a strong association in cognitive structure, perhaps relying on episodic memory (Squire, Knowlton, & Musen, 1997). Similarly, mnemonic devices (whether their own, or an association offered by teachers) may well be relevant to recall. This could explain the rationale in item 4 with a 'cultural reference': "the two substances came together as one, 'two become one' (the Spice Girls' song)".

Some responses may reflect the students' attempts to visualise the reactions by running a mental simulation at the level of particles: "the potassium takes some of the nitric acid particles and the hydroxide becomes water" (item 1). Other descriptions could simply be an attempt to offer some post-hoc basis for their chosen answer, or may just be an attempt to describe their applications of other strategies through a descriptive mode. For example, one student explained the correct response (*potassium nitrate*) in item 1 in terms that could be read as referring to particles: "the oxygen and hydrogen have been displaced by the nitric acid which joined onto the potassium oxygen and hydrogen make water".

As with previous strategies discussed, it is not uncommon for a correct response to be based upon dubious, confused or clearly incorrect chemical knowledge: e.g. "the potassium atoms fuse with the nitric acid atoms to create potassium nitrate" (item 1).

Student responses including narratives often also drew on other strategies identified here. For example, one correct response on item 3 was supported by the rationale:

> "sulphur is more reactive than carbon, so zinc joins with sulphur rather than carbon. The water in the carbonate gets released when zinc leaves it. The carbon joins with oxygen".

Starting from the behaviour strategy (comparing reactivity), the reaction is explained in terms of three steps - zinc joining sulphur; carbonate releasing water; carbon and oxygen joining – none of which relate to the actual mechanism of the reaction.

Ignorance about the way compounds can be 'parsed' was quite common. In particular, the way compound ions (such as nitrate and sulphate) are commonly unchanged in chemical processes was not recognised in some students' narratives, e.g. (for item 1):

> "the nitrogen from the nitric acid reacts with the potassium and the oxygen to form potassium nitrate. T[he] water comes from the hydrogen in the acid and in the hydroxide and the oxygen comes from the hydroxide"

Intuitive Strategy

The final strategy that was explicit in students' rationales was that of guessing; this could be considered equivalent to a random answer but is perhaps better considered an answer that is reached without any *conscious* rationale. The label 'intuitive' strategy, is perhaps well illustrated by the rationale: "calcium and chlorine make calcium chloride. That is my reasoning. There's no other answer" (item 4). This could almost be paraphrased as 'it is obvious' (Watts & Taber, 1996). Certainly to someone familiar with the patterns of chemistry, it is easier to answer this item, than to explain the logic of the answer.

Guessing was not a popularly reported strategy but as with 'recall', it may well be that a proportion of the responses with no rationales offered were based on guesswork. In one sense this strategy takes us full circle back to the Recall Strategy. In terms of conscious thought, a remembered or a guessed answer both seem to appear in consciousness without any logical preamble, although those designated as guesses did seem more commonly associated with incorrect responses: *salt*, *nitric hydroxide* (item 1); *nitrogen*, *copper sulphate* (item 2); *sulphur dioxide*, *hydrochloric acid*; *zinc* (item 3); *magnesium*, *magnesium acid*, *magnesium oxide*, *magnesium hydroxide* (item 5).

Selection of strategies

Sometimes, the same individual would elect the same approach in different questions with varying results (see Table 8). One student who claimed "I am guessing" to all 5 items got each correct (reinforcing our point above that 'guesses' may be based on more than random choices), but other students who guessed throughout had lower 'hit' rates.

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Table 8: Examples of similar strategies applied by the same student with differing success

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One student applied a displacement reaction schema to four of the items, being more successful on two items than the others (see Table 8). Another student accounted for correct answers on three items in terms of relative reactivity, but in two cases (items 3 and 4) the logic was highly dubious:

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- item 2 – [*copper nitrate solution*] “zinc is more reactive than copper and will react with the nitrate solution”
- item 3 – [*sulphuric* acid] “zinc is more reactive than sulphur and will displace the zinc - the sulphuric has nowhere to go but join with the zinc”
- item 4 - [*calcium chloride*] “the calcium is more reactive than the chlorine and the chlorine has nowhere to go but onto the calcium”

Discussion

The preceding analysis was based upon interpretation of students’ reports of their reasoning in undertaking a particular type of task (completing word equations with a single missing term). In terms of exploring thinking, such an approach is limited by the extent to which:

- students are aware of their thinking
- students are motivated to give full accounts
- students are able to clearly explain their rationales

Notwithstanding these considerations, the examination of over a thousand accounts from a sample of three hundred students has allowed a model to be developed of the ways that students’ accounts suggest that they go about this task.

Coordinating knowledge in working with word equations

It is clear from the analysis above that the strategies identified may be used in combination, and that they also vary in the extent to which they rely on recall of

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specific information or more general trends. Indeed, student accounts of their rationales suggest these strategies call upon chemical knowledge at three levels of generality:

- knowledge of chemical particulars
- knowledge of chemical patterns
- knowledge of chemical principles

There is no single preferred strategy that can be considered the 'best' approach: this will depend upon the relevant knowledge students have available in a particular case.

The most straightforward approach is based upon application of knowledge of chemical particulars: i.e. simply to recall the reaction or its equation. When recall is accurate, this will be a simple and effective way of finding the answer. However, inaccurate recall will lead to a wrong answer, so this approach may be high-risk.

When the student does not know the specific equation they can draw upon knowledge of chemical patterns at different levels of generality:

- knowledge of reaction types: schemata such as acid + metal → salt + water
- knowledge of classes of substance: e.g. acids contain hydrogen; salts have a metal and a non-metal component
- knowledge of particular substances: e.g. sulphuric acid gives salts which are sulphates; salts of chlorine are called chlorides

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Generally strategies based on applying chemical patterns underdetermine the answer, but can help to limit the set of feasible responses.

The schema strategy seems to be an especially powerful one, as it was seldom associated with incorrect answers when the appropriate general equation was recalled. The data *suggest* that the identification of the correct reaction type often allowed the student to complete the task without further conscious thought. It seems that the correct salt, or acid, or metal etc. may well be selected by some students without conscious effort once the required slot of the appropriate schema has been identified, i.e. "automatic intuitive processes may co-occur with attentional logical thinking" (Cohen, 1983: 128). Due to the methodology used here, this remains a conjecture, but - if correct - suggests some of these students were beginning to demonstrate aspects of 'expert' thinking.

The strategy based upon a conservation principle allowed students to place bounds on the elements represented in the missing term. It is not clear if students appreciated the logical requirements here - that generally the strategy does not give a definitive list of elements but rather those that logically must be represented, and those that could (but need not) be represented in the missing term. That is, by itself this strategy divides the chemical elements into three groups: those we must include, those we could include, and those that we must exclude.

So again, successful application of the strategy usually involves coordination of one chemical pattern, here a universally applicable one (conservation of the elements represented in the reactants), with other knowledge that enables one of several possible responses to be selected - although again there is some suggestion in the data that use of the conservation principle may sometimes allow the correct response to be identified without explicit conscious use of the necessary auxiliary information.

Some students reported guessing their answers, with mixed results. Guessing is not a strategy that would normally be recommended to students, but if a guess is understood to be accessing subconscious thinking, then it would seem to be something that was in practice incorporated in the application of other strategies.

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Further research

Aspects of student thinking that are subconscious are not open to ready investigation. Indeed it may well be that subconscious processing through neural nets cannot be related to logical chains of propositions (Dawson, 1998). However, the model offered here could certainly be explored through more revealing methodologies (if necessarily with smaller samples). Both talk-aloud protocols and semi-structured interview techniques could potentially clarify when steps in task completion are omitted from reports because they are tacit, rather than because student have difficult expressing them in writing, are not motivated to give full reports, or did not consider that the detail should be included. To the extent that such missing steps may possibly reflect a transition from novice to expert thinking, longitudinal research in this topic could be very informative.

More in-depth approaches may also illumine those responses where the reported rationale does not seem consistent with the students' answer. One particular feature of interest is students accounting for their responses in terms of presenting a feasible 'story' of the reaction process. These narratives were often chemically dubious, and it

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would be interesting to know if (or when) they were attempts at chemical thought experiments, using visualisation to simulate chemical processes (Gilbert, 2005), rather than post-hoc attempts to rationalise an answer that was presented unadorned to consciousness. Similarly it would be interesting to know why apparently irrelevant information is included in some student rationales, and whether this indicates reliance on episodic memory (Squire et al., 1997) to access abstract conceptual knowledge in chemistry. Such studies could include a greater range of tasks involving the representation of chemical reactions in word and formulae equations. In view of the centrality of equations in teaching and learning chemistry, a better understanding of the range and depth of student thinking about and with equations would be very useful to inform pedagogy.

Limited conceptual foundations for appreciating the mediating role of chemical equations

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In the introductory section of the paper we suggested there were reasons to expect students to find learning about chemical equations to be problematic. Previous research has suggested that learners often develop alternative conceptions of the nature of chemical change that are inconsistent with scientific and curriculum models (Ahtee & Varjola, 1998; Andersson, 1986; Briggs & Holding, 1986; Cavallo et al., 2003; Hesse & Anderson, 1992; Johnson, 2000). The scientific concept of 'substance' is a basic prerequisite for understanding the science of chemistry, and is essential to develop the canonical notion of chemical change, but is not readily acquired by many learners.

Our database for this study offers many instances of comments suggesting that students have not appreciated the essence of a chemical substance, as for example the references in Table 5 that show students considering potassium hydroxide to contain potassium as a discrete substance. Such fundamental knowledge deficits might seem incongruous with the relatively high success rate of students in identifying the missing terms (the examples cited in Table 5 refer to students giving a correct identification), but it has been reported that students who are successful in school science may manage to pass public examinations whilst holding very tenuous understandings of basic chemical concepts and principles (Taber, 1996).

We also referred in the introduction to the role of ‘particle’ models in developing an understanding of the ‘substance’ concept (Johnson, 2002; Taber, 2002b), but noted how acquiring scientifically acceptable models of the submicroscopic realm was itself problematic for many learners (Ault, Novak, & Gowin, 1984; Griffiths & Preston, 1992; Nussbaum & Novick, 1982; Taber, 2001a; García Franco & Taber, Accepted for publication). Again our database offered examples of how students may readily adopt notions of atoms and molecules that are inconsistent with scientific concepts. The reference quoted in Table 7 of how “zinc atoms fuse with the sulphuric acid atoms” was again associated with a correct answer.

The frequent shifting between the macroscopic, symbolic and submicroscopic levels in chemistry teaching is considered to increase the cognitive demand on learners (Gilbert & Treagust, In press; Johnstone, 1991). Chemical equations (i.e. at the symbolic level) potentially mediate chemistry at the macroscopic and submicroscopic levels (Taber, In press). However such mediation can only effectively support learning where students have chemically sound models of what is meant by substance and chemical change and how these concepts are understood at those levels, and the present study reiterates findings from that existing research that suggests this is often not so. Indeed, in many narrative rationales (see the examples in Table 7) it is not clear whether students are referring to substances or particles, or indeed whether such a distinction is even relevant to their thinking.

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Informing teaching

The present research set out to explore why students make mistakes when asked to undertake a relatively basic task concerning word equations, and - in particular - the nature of working with word equations from the student perspective. The analysis suggests that

- unless students have full specific knowledge of a particular reaction, they need to call upon a strategy that involves the coordination of several chemical knowledge facets;
- there are several strategies which can be successfully employed, drawing upon chemical knowledge of different levels of generality/abstraction;
- the choice of a strategy has to be made on a case-by-case basis depending upon which relevant information is available.

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This may not seem helpful for informing pedagogy, but at the very least it may help teachers to appreciate how a task that seems simple to the expert may actually be quite complex when analysed at the resolution appropriate for the learner.

Although the present study has inherent limitations, the analysis presented here would suggest that teachers should take time to explore the possible strategies, and their strengths and limitations with students. Given that no rationale at all was offered for almost a third of the responses offered by this sample of learners, this may be an excellent topic for developing students' metacognition and problem-solving skills (Phang, 2006), i.e. getting them to think about the nature of the task they face and possible approaches to its solution. In particular, the present research suggests that this (apparently) simple type of task may best be approached by some form of meta-strategy - such as that offered in figure 1.

Figure 1: An outline of a model approach to the task of completing word equations

Figure 1 summarises the different strategies available to students, and sets out a meta-strategy that would help students decide which strategy was a good 'starting point' for tackling particular questions. It is not possible to offer more specific guidance on this, as the best strategy will depend upon the specific question and the relevant knowledge a particular student has available. Most of the strategies consist of several steps that involve accessing particular chemical knowledge, and then applying that knowledge (i.e. logical processing – making deductions). Depending upon the strategy, different types of knowledge may have to be coordinated.

The model then relies upon 'strategic' knowledge (knowledge of the different strategies – which background knowledge to access and how to process it within a strategy); 'tactical' knowledge (the knowledge of chemical principles, patterns and processes that allow answers to be found through the strategies); a meta-strategy (to know when to call upon different strategies); and sufficient 'meta-knowledge' to be aware of which tactical knowledge is available to make decisions relating to the meta-strategic scheme.

It is not suggested that teachers should explicitly teach this strategy to students, at least certainly not in this form. However, this could be more than a useful aide-mémoire to help the teacher to keep in mind the complexity of a task (that has become automated and largely intuitive for the expert) when seen at the novice's resolution. It is suggested that teachers should at least explicitly explore with students how successful working with word equations is contingent on coordinating strategic and tactical knowledge: that the best way of approaching the problem depends upon what relevant chemical knowledge can be accessed in specific cases.

Conclusion

As chemical equations are ubiquitous in teaching and learning chemistry, it is hoped that the present analysis may be useful in informing teachers in an area where many students struggle. Although the present research was based on a set of completion tasks designed around chemistry likely to be familiar to secondary students, it is considered that the need for such a meta-strategic approach may be even greater when students are asked to respond to inherently more demanding tasks involving chemical equations.

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Figure 1: An outline of a model approach to the task of completing word equations

Meta-strategy: Do you know the equation/reaction? If so, go to S1. If not, continue.

Do you recognise the general type of reaction? If so, go to S2. If not, continue.

Do you know anything about the way these chemicals behave in reactions? See questions, under S3. If not, continue.

Can you identify the elements represented on each side of the equation? If so, go to S4, If not, continue.

Go to S5

Strategy S1:
a: **write out the equation**
b: identify missing term
note: memory can let us down, so
c: use S2-S4 to check your answer

Strategy S3:
a: **make a list of the known information about the susbtances in the reaction that may be relevant**;
b: **identify the classes of substance known to be present**;
c: **make a list of information about the classes of substances known to be present that may be relevant**;
d: **identify anypatterns in the names of chemical susbtances that may be relevant**
e: decide if you have enough information to identify the answer
f: if so, check your answer is consistent with S4; otherwise see if S4 helps.

Strategy S5: if all else fails, guess
note - try to make it an informed guess - follow any hunches you have about the answer

Strategy S2:
a: **write out the general equation for this type of reaction**
b: match the known substances against the classes of substance in the general equation
c: identify the class of the missing substance
d: work out the identify of the missing substance - refer to S3 and S4 to help with this

Strategy S4:
a: **make a list of all the elements that are represented in the reactants, and a list of all the elements that are represented in the products**;
b: compare the two lists, and so identify any elements that must be represented in the mising term;
c: **list all the substances that include these elements, plus the other elements that could be included**;
d: decide which of these substances are consistent with other information available (i.e. from S2, S3)
e: if more than one possible answer, go to S5

notes:
meta-strategy guides on where to start
most strategies involve a sequence of steps:
some steps involve processing information/decisions (underlined)
some steps involve ***accessing specific chemical knowledge*** *(bold)*

Coordinating procedural and conceptual knowledge to make sense of word equations: understanding the complexity of a 'simple' completion task at the learner's resolution

Tables

Table 1: Completing the word equation

item	Correct response	Number of responses	Correct	Nearly correct	Incorrect	Non-responses
1	potassium nitrate	283	211 (75%)	2 (1%)	70 (25%)	17
2	copper nitrate solution	289	43 (15%)	184 (64%)	62 (21%)	11
3	sulphuric [acid]	281	225 (80%)	8 (3%)	48 (17%)	19
4	calcium chloride	279	248 (89%)	11 (4%)	20 (7%)	21
5	magnesium chloride	281	189 (67%)	9 (3%)	83 (30%)	19
Total		1413	916 (65%)	214 (15%)	283 (20%)	87

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Table 2: Examples of student rationales based on type of reaction schemata.

item	rationale for correct response
1	acid + metal hydroxide = salt + water is the general in equation for the question
	the acid is neutralized by the alkali to make water and a salt will be made
	when an alkali and an acid are put together they form a salt and water - a salt is a combination of the alkali and acid
	I know nitric acid makes nitrate and acid reacting with an alkali produces a salt and water
	an acid and a base react to create the salt and water. Potassium hydroxide is a base. The salt produced is potassium nitrate
	acid + alkali = salt + water, potassium is first bit - the metal, nitrate because nitric acid
	when an acid (nitric acid) and a base (potassium hydroxide) react they produce a salt which in this case is potassium nitrate and water
2	copper nitrate: this is a displacement reaction, zinc is higher in the reactivity series so it displaces copper
	copper nitrate: the reaction shown is a displacement reaction and zinc is more reactive than copper
	when a salt is combined with a higher metal of reactivity the reactive metal will displace the other
3	acid + metal carbonate = salt + water + carbon dioxide
	when an acid combines with a carbonate then a salt is formed along with carbon dioxide from the carbonate and water
	acid + carbonate = salt + water + carbon dioxide, and sulphate is the salt of sulphuric acid
4	calcium and chlorine will react together to make calcium chloride (as there is no acid to make a salt included or any other chemical) it's just a simple chemical reaction
5	acid + metal = salt + hydrogen
	reaction between a metal and an acid, a salt and hydrogen gas are released
	metal + acid = salt + hydrogen, and chloride is the salt of hydrochloric acid
	when a metal and an acid are put together salt and hydrogen are created the salt is created from the acid and metal and the hydrogen is given off through this process

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acid + metal carbonate = salt + water + carbon dioxide and the sulphate in the salt comes from the sulphuric acid¶

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when acids react with metal they form hydrogen (from the acid). Also from my knowledge of the reactivity series I know magnesium will react with acid

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Table 3: Student rationales based on patterns in chemical language

item	rationale for correct response
1	the first word of each compounds with three elements in end in ATE and they ALWAYS have oxygen in in most word equations you just have to flip round the words to get the right equation potassium hydroxide and nitric acid go together to make potassium nitrate not nitric potassium because the acid always goes last when it mixed together you take the name of the acid and put it with either the metal/oxide this makes a salt and takes the name of the oxide and acid
2	I switched the copper and the zinc this is what's normally is done in an equation
3	because sulphate is a chemical reaction and they sound the same sulphate is sulphuric acid's name when it is made into a solution the –er changes into an –ate. Therefore sulpher changes to sulphate
4	you have to change the chlor ‘ine’ to ‘ide’ to make a solution chlorine and always becomes chloride, whenever there are two things together the ending is –ide it is relatively obvious that if t[w]o substances are combined and we know they form one compound then that simply like in math X x Y = XY calcium is the more reactive of the two so it goes first in the final equation they would mix and chlorine calciumide sounds wrong just basically that the calcium and the chlorine will mix and the calcium will stay the same but the chlorine will turn to chloride

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Table 4: Examples of student rationales for correct and incorrect responses based upon patterns in behaviour of classes of substance

item	rationale for correct response	incorrect response – and rationale
1	something + a hydroxide usually goes to nitrate + water potassium hydroxide is a salt [sic] and in general salts react with acid and let off hydrogen which sometimes forms oxygen	*hydrogen* - acids always contain hydrogen and because hydrogen is often given off when an acid reacts *hydrogen* - all reactions with acids produce water and hydrogen *potassium sulphate* - acid is usually produce some sort of sulphate *nitric oxide* - there is oxide in hydroxide and that is usually the case *potassium nitride* - the potassium will join with the nitride as they are metals
2	when a metal reacts with a salt made from metal, the things attached to the two metals i.e. nitrogen 'swap' partners to make zinc nitrate you need to have nitrate so copper nitrate would be a good one to use	*nitric acid* - zinc and nitric acid gives us a zinc nitrate solution *nitric acid* - you have a 'nitrate solution' at the end of it *nitrogen* - nitrates come from nitrogen *nitric acid* - only a nitrate solution could be formed by a nitric acid *nitrate* - zinc + nitrate = zinc nitrate. If you join the two liquids together you make them join together as a word *nitrogen + oxygen* - nitrate consists of nitrogen and oxygen
3	zinc sulphate tells you (e.g. sulphate) tells you which acid is involved in the experiment it has zinc sulphate which suggests it is an acid which has Sulphur in it sulphuric acid makes carbon dioxide	*hydrochloric* – we use hydrochloric acid a lot *hydrochloric* – hydrochloric acid always makes a carbonate *hydrochloric* - you need hydrogen to make water so it must be hydrochloric acid
4		*calcium + chlorine* - Two metals do not react unless there is something to make them react *calcium chloride solution* - when two elements are put together then they form a solution with both substances put together
5	when metals react with acid they give off hydrogen the magnesium being a metal will join with the chlorine to form the chloride and the hydrogen will become isolated when acid is with a substance it reacts. Hydrogen gas, in every acid, is released	*magnesium oxide* - the magnesium takes the oxygen from the acid and also produces hydrogen because it is a metal

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Table 5: Examples of students' rationales for correct and incorrect responses based upon chemical behaviour of substances.

item	rationale for correct response	incorrect response – and rationale
1	in the potassium [sic] has displaced the nitric acid as it is higher in the reactivity series than nitrogen when the two are mixed the potassium [sic] is more reactive and will take the nitrate from nitric acid the potassium [sic] is very reactive so it will react with the acid leaving behind the water the hydroxide becomes water and potassium [sic] is stronger than the nitrate (displaces it) so it forms onto the potassium hydroxide forms water so the potassium [sic] has a greater affinity with the nitric acid	*potassium nitric acid* - potassium is more reactive than nitric acid *potassium hydroxide* - potassium hydroxide is more reactive than nitric acid *potassium* - the potassium will displace the nitgen [sic] due to the fact that it is more reactive *potassium oxide* - potassium is more reactive than nitrogen acid so it will keep the oxygen and the hyd- part becomes water: hydroxide= oxygen + water *potassium acid* - potassium is higher up the reactivity series therefore the one that is stronger will gain the acid *nitric hydroxide* - you add nitric and hydroxide together to make nitric hydroxide
2	zinc is higher in the reactivity series than copper, so the zinc takes the nitrate from the copper the zinc is more reactive than copper so it displaces the copper from the nitrate	*copper nitric* - zinc is more reactive than copper so the zinc steals nitric of copper *copper nitride solution* - zinc is more reactive than copper so it replaces it
3	the sulphur is more reactive than carbon and so it will take the zinc from it adding the strong sulphuric acid to the weak salt (zinc carbonate) causes the carbonate to be changed into a sulphate and carbon dioxide and water to be given off that is the only acid that gives you a metal sulphate	*carbon oxide* - carbon oxide and carbonate gives carbon dioxide
4	the calcium is more reactive than the chlorine so it takes over it the calcium displaces the chlorine because it is higher in reactivity calcium is a metal and chlorine is reasonably acidic chlorine when it mixed with a chemical (metal) become chloride so calcium + chloride = calcium chloride Chlorine has oxygen in it when any two elements react with chlorine (calcium + oxygen in this case) it makes a chloride	*calcium carbonate* - chlorine contains carbon *calcium carbonate* - when you heat both calcium and chlorine you get calcium carbonate, where –ate is the oxygen *calcium + chlorine* - the chlorine does not react with the calcium
5	the magnesium is higher up the reactivity series than hydrogen so steals the chlorine to form hydrogen magnesium reacts better with a gas (hydrogen) rather than an acid. It displaces it the magnesium displaces the chloride from the hydrochloric acid as it is more reactive magnesium is more reactive than hydrogen so the chlorine leaves the hydrogen to react with the magnesium chloride and magnesium create hydrogen when bonded	*magnesium oxide* - the magnesium takes the oxygen off the hydrogen as it is more reactive *magnesium* - magnesium shouldn't react with hydrochloric acid *magnesium* - hydrogen comes from the acid *magnesium oxide* - because the magnesium has to join something to react so it joins the oxygen because all the substances have converted and water has hydrogen in it so oxygen is left *magnesium hydrate* - when hydrochloric acid reacts with another its changes to hydrate

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Table 6: Examples of student's reported rationales for correct and incorrect responses based on patterns of behaviour of specific substances¶

Table 6: Examples of students' rationales for correct and incorrect responses based upon the application of a conservation principle

item	rationale for correct response	incorrect response – and rationale
1	in side one there was O_2, H, K and nitric acid. On side two there is K, nitrogen + O_2 (= ate) and H_2O water. I know that all acid contain H and if its combines with hydroxide and I only have one space to fill out the only elements to left to combine water contains hydrogen and oxygen. This leaves potassium and nitrogen which form potassium nitrate when they react together I added the ingredients together	*potassium* - there is potassium left in the equation and this would be left after the reaction and water *potassium nitride* - you take the oxygen from the acid to make water which leaves you with potassium and nitrogen *potassium nitric* - the water is made by the hydroxide and acid so potassium and nitric is all that's left over. *potassium nitrite* - this is the equation [sic] that is left over and it works
2	there is oxygen zinc, copper and nitrogen in the products area. Therefore the answer must contain copper, nitrogen and oxygen. This is copper nitrate in the result there is zinc and copper and to make that you need zinc and copper in the first place copper has to go on that side and where does the nitrogen come from? Therefore that needs to be on that side as well	*nitrate solution* - because nitrate solution is the chemical that is missing in the first bit *nitric acid* - the nitrogen has to be present in the first part of the equation *nitrogen and copper oxide* - there has to be copper and oxygen and nitrogen and if the copper doesn't change then it shouldn't be there as it is not needed *nitrate* - zinc plus nitrate is the only way you're going to get a zinc nitrate solution
3	everything on one side has to go onto the other sulphate is in the residue and therefore must be in the first equation zinc sulphate is a product and so there must be sulphur in the acid which makes it sulphuric acid because you end up with zinc sulphide [sic] and I think it formed because you cannot have Sulphur anywhere else in the reaction, it has to come from somewhere the zinc, oxygen and carbon had been used up, leaving sulphur	*hydroxide* - when looking at the I can tell what is missing from either side as it is meant to be equal *sulphate* - sulphate is mentioned in the answer but not the question *hydrochloric* - zinc and carbon are already present which leaves the water which needs *hydrochloric* - to have H_2O and CO_2 on the product from HCl comes an H and a C this means that it has to be on the other side. *hydrochloric* -Water has hydrogen and it is the only one that makes sense
5	hydroCHLORIC so chlorine, magnesium chloride because magnesium must go somewhere something has to happen to the magnesium and the chlorine from the left so I think it becomes magnesium chloride the total quantity of substances must be the same before and after the reaction. There is one blank space so the Mg and Cl must form an ionic compound if the balance is to be maintained	*magnesium oxide* - the hydrochloric becomes hydrogen so the magnesium must become something *magnesium oxide* - magnesium and oxygen (from the HCl) were the only two substances that needed to be balanced on the other side *magnesium* - it is the only thing left *magnesium chlorate* - *the hydrogen is used up* the leaving chlorate and magnesium *magnesium acid* - magnesium is in the equation

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Deleted: *nitric acid* - there is a nitrate present in the second of the equation so I figured that must be some sort of nitric acid in the first¶
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Table 7: Examples of students' rationales for correct and incorrect responses supported by narratives

item	rationale for correct response	incorrect response – and rationale
1	the hydrogen in an acid 'splits' off the acid molecule in this sort of reaction. If its combines with the hydroxide it will make water ($H^+ + OH^- = H_20$). Therefore the K^+ must combine with the NO_3^- the nitric acid mixes with the potassium hydroxide and the nitrogen goes from the acid to the potassium the nitrate in the acid pushes the hydroxide away from the potassium the nitric acid has reacted with the potassium making potassium nitrate. The heat produced turns the hydroxide part into water the potassium absorbs the nitric acid to make it nitrate the potassium stays the same and the nitrogen combines with the oxygen to form nitrate	*potassium acid* - the hydroxide has joined with the nitric acid to water? *potassium nitrate + hydrogen* - potassium plus the nitric acid makes potassium nitrates and the hydroxide mixes to make the water *potassium nitroxide* - the nitric acid will mix with the potassium hydroxide and will give nitroxide with the potassium *nitric hydroxide acid* - because nitric acid takes over the potassium nitrogen oxide - the nitrogen comes from the nitric acid which is reacting with the potassium hydroxide which provides the oxide
2	the zinc cancelled out the copper the copper is weak so the zinc would 'grab' the nitrate solution and 'take' it for itself	*copper oxide* - the zinc has displaced the oxygen from the copper oxide *copper carbonate* - the carbonate leaves the copper *nitrogen + copper oxide* - the copper's oxygen was stolen and put with the nitrogen to make -ate
3	zinc atoms fuse with the sulphuric acid atoms to create zinc sulphate the zinc reacts with the acid to make zinc sulphate and the copper reacts with the oxygen in the air to make carbon dioxide the substances have switched partners therefore zinc carbonate and sulphuric is split up to form zinc sulphate and water + CO_2	*hydrochloric* - the hydrochloric acid (hydrogen) mixes with oxygen to create water *hydrochloric* - the hydrochloric acid would react making water and CO_2
4	the calcium would dissolve in the chlorine giving you a calcium chloride solution the chlorine mixes with the calcium and dissolves it to become joined when both elements combine oxygen is gained by the chlorine calcium takes the electrons from the chlorine	*calcium chlorate* - the calcium will absorb the chlorine gas *calcium chlorine solution* - the calcium will dissolve into the chlorine *calcium carbonate* - the chlorine joins the calcium to make calcium carbonate
5	the hydrochloric acid gives of[f] chlorine which react with magnesium and it gives of hydrogen as well	

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Table 8: Examples of strategies applied by the same student with differing success

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rationale for correct responses	rationale and incorrect responses
because calcium will displace chlorine (item 4)	zinc will displace copper sulphate (*copper sulphate* - item 2)
when zinc reacts with nitric acid it takes place of copper, zinc being more reactive (item 2) sulphuric acid is more reactive with zinc than copper and will take its place in the equation (item 3)	because the nitric acid is less reactive than potassium so potassium will push the hydroxide out (*potassium hydroxide* - item 1) magnesium will react better with the chloric than hydrogen, taking its place (*magnesium chloric acid* - item 5)
zinc is more reactive than copper so it displaces it (item 2) magnesium displaces hydrogen because it is more reactive (item 5)	potassium is more reactive than nitric so displaces it (*potassium acid* – item 1)
it is what I have been taught and learned and sulphuric acid and zinc make that if you mix them (item 3)	this is what we have learned (*nitrates and phosphates* - item 1)
nitric acid goes to nitrate and potassium is the first part (item 1)	nitric goes to nitrate solution and zinc is a metal (*nitric acid* – item 2)
sulphuric acid is needed to make/form zinc sulphate (item 3) and I took a wild guess (item 2)	you need nitric acid to make zinc nitrate solution (*nitric acid* – item 2) and I took a wild guess (*magnesium oxide* - item 5)
when an acid and a base reacts the metal that is higher in the reactivity series displaces the less reactive metal (item 1)	the zinc is more reactive so displaces the nitrogen (*nitric acid* – item 2)

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item [correct response]	rationale for correct response	incorrect response – and rationale
1 [*potassium nitrate*]	nitric becomes nitrate so put after the potassium makes potassium nitrate hydroxide forms water so the potassium [sic] has a greater affinity with the nitric acid when potassium [sic] reacts with an acid the nitric turns into nitrate	*nitrogen oxide* - if you add these two you get nitrogen oxide *nitric hydroxide* - you add nitric and hydroxide together to make nitric hydroxide
3 [*sulphuric*]	that is the only acid that gives you a metal sulphate	*carbon oxide* - carbon oxide and carbonate gives carbon dioxide
4 [*calcium chloride*]	calcium is a metal and chlorine is reasonably acidic chlorine when it mixed with a chemical (metal) become chloride so calcium + chloride = calcium chloride the elements react to gain a full outer electrons shell causing the elements to become positive and negative ions and opposites attract they both react and become calcium chloride because there is no oxygen - otherwise it would form calcium chlorate Chlorine has oxygen in it when any two elements react with chlorine (calcium + oxygen in this case) it makes a chloride	*calcium carbonate* - chlorine contains carbon *calcium carbonate* - when you heat both calcium and chlorine you get calcium carbonate, where –ate is the oxygen *calcium + chlorine* - the chlorine does not react with the calcium
5 [*magnesium chloride*]	the magnesium becomes a chloride when mixed with hydrochloric acid. Just like it would be a sulphate when mixed with sulphuric acid chloride and magnesium create hydrogen when bonded the acid when chemically changed becomes chloride and the magnesium is mixed with it	*magnesium* - magnesium shouldn't react with hydrochloric acid *magnesium* - hydrogen comes from the acid *magnesium oxide* - because the magnesium has to join something to react so it joins the oxygen because all the substances have converted and water has hydrogen in it so oxygen is left *magnesium hydrate* - when hydrochloric acid reacts with another its changes to hydrate

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4 [*calcium chloride*]	the total quantity of substances must be the same before and after the reaction. There is one blank space so the Mg and Cl must form an ionic compound if the balance is to be maintained	

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the zinc sulphate had to come from sulphur, so sulphuric acid contains the sulphur

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[*magnesium chloride*]

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the magnesium and the chlorine kind of disappeared so I used them

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the hydrogen in hydrochloric acid is released as hydrogen so you are left with magnesium and chlorine, hence magnesium chloride being a product along with hydrogen

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